Minimum Variance Control for Acoustically-Compact Plants

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(Received 10 December 1999; revised 27 March 2000; accepted 15 June 2000)

The objective of the paper is to present and thoroughly examine some concepts of noise control algorithms for acoustically-compact plants. Acoustically-compact plants deserve to be considered as a special group of noise control plants. They are distinguished by the fact that, due to the geometrical arrangement of the loudspeakers and microphones used in the digital control, the transmission times of the acoustic waves are shorter than the transmission times of the corresponding electrical signals. For other electro-acoustic plants, where a reference signal is accessible via a suitable mechanical, electrical or optical transducer and the controller can be causal, feedforward systems can be designed with much success. Otherwise, feedback systems are normally used. For acoustically-compact plants, no optimal controller can be causal since it has to be designed to predict signals with different delays. In this paper minimum variance algorithms based on different control structures: feedforward, feedback (classical and internal model control), and combined (three versions) are considered. First, performance limitations are described. Then the algorithms are analysed theoretically, verified by simulations and finally tested on a real-world device. Features of the algorithms employed for other electro-acoustic plants are also discussed.

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1. INTRODUCTION

It is known that local active noise control (ANC) near the secondary source enables creation of large zones of quiet and is technologically feasible for almost all cases where ANC is demanded.[1] Besides, it requires the smallest amount of energy to drive the secondary source and therefore it is economically efficient. If, additionally, a reference sensor is placed also very close to the secondary source, it is possible to define in digital ANC a group of plants further referred to as acoustically-compact plants. More precisely, by acoustically-compact plants (ACP) are understood as electro-acoustic plants (or rather, devices) for which transmission times of electrical signals from both the reference and the error microphones to the secondary source are longer than the transmission times of acoustic waves between points in which these components are placed (see Fig. 1).[2] Such a time relation is possible only in digital control (a control system with a continuous plant and digital controller is referred to as a sampled-data system) and it generally depends on the sampling frequency. It is caused by the necessity of employing analogue filters (anti-aliasing and reconstruction) that introduce significant phase lags, and by one sampling interval required to drive the secondary source synchronously.[3] Consequently the feature discussed significantly influences properties of the plants and the performance of the ANC algorithms. ACPs are said to require non-causal actions. In turn, all the benefits related to the small distance between the secondary source and the error sensor (short transmission time and relatively large zones of quiet) can be drawn, although some negative aspects of this also emerge (nonlinearities and non-minimum phase phenomena).[2] It should be noticed that in such plants the microphones are placed in the near-field of the vibrating secondary source surface, where energy is stored.[4] Examples of ACPs are: active personal hearing protection devices, active headrests, silent lamps, etc.

2. CONTROL OF COMPACT ACOUSTIC PLANTS

In this paper, controllers minimising the energy of the primary acoustic noise, in fact – variance of the system output, are designed. Such a strategy is referred to as minimum variance control – MVC. The primary acoustic noise has energy incomparably higher than the energy of the measurement noise and acoustic background. Thus, only the primary noise will be considered as the output disturbance of the plant. The disturbance, if it is random, can be described as white noise, $e(i)$ (with variance λ^2), filtered by a so-called disturbance-shaping filter. It is very advantageous, from the point of view of the optimal controller design and further interpretations, to employ here a minimum phase (assured by the estimation procedure) FIR filter $C(z^{-1})$ with free-required length.[2,5] Therefore, from now on the following system output equation will be dealt with:

$$y(i) = \underbrace{z^{-k}\frac{B(z^{-1})}{A(z^{-1})}}_{P(z^{-1})} u(i) + C(z^{-1})e(i), \qquad (1)$$

where the first term on the right-hand-side (RHS) of Eq. (1) models the plant identified off-line (k is the discrete time delay) and the second term models the primary noise, $y_P(i)$, to be attenuated (z^{-1} is the backward shift operator and it will be further omitted to simplify the notation). This differs significantly from designs met in the literature, where such an equation describes the ARX or ARMAX plant model identified off-line and no other exogenous noise is taken into account.